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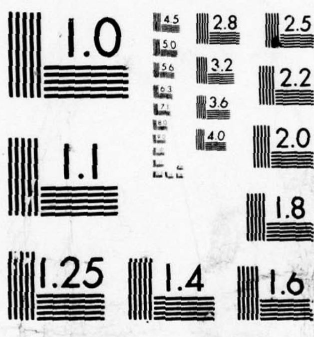

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SCHOOL OF ENGINEERING AND APPLIED SCIENCE

UNIVERSITY OF VIRGINIA

Charlottesville, Virginia 22901

A Final Technical Report

MAGNUS EFFECT ON SPINNING BODIES OF REVOLUTION

Submitted to:

Commanding Officer
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709

Submitted by:

D. S. Joshi
I. D. Jacobson
J. B. Morton
P. A. Torpey

Grant Number
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May 1979

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A Final Technical Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
A numerical finite difference method is developed to solve the three dimensional laminar/turbulent boundary layer equations on a spinning body of revolution at an angle of attack in supersonic flow. Influence of asymmetric transition and the presence of mixed boundary layers is considered to predict Magnus forces and moments. Several contributions to the Magnus effects are considered. These include asymmetric boundary layer displacement thickness, centrifugal pressure, and primary and cross flow wall shear stresses. Boundary layer structure defined by asymmetric transition is shown to critically influence

the aerodynamic forces and moments on bodies of revolution. Important variables in the flow field are identified by considering variations of spin rate, Mach number, angle of attack and length of the body. Comparisons are made with experimental data and other theoretical analyses.

ABSTRACT

A numerical finite difference method is developed to solve the three dimensional laminar/turbulent boundary layer equations on a spinning body of revolution at an angle of attack in supersonic flow. Influence of asymmetric transition and the presence of mixed boundary layers is considered to predict Magnus forces and moments. Several contributions to the Magnus effects are considered. These include asymmetric boundary layer displacement thickness, centrifugal pressure, and primary and cross flow wall shear stress. Boundary layer structure defined by asymmetric transition is shown to critically influence the aerodynamic forces and moments on bodies of revolution. Important variables in the flow field are identified by considering variations of spin rate, Mach number, angle of attack and length of the body. Comparisons are made with experimental data and other theoretical analyses.

INTRODUCTION

The study of three dimensional boundary layers on rotating bodies of revolution has attracted considerable attention in the past because of its application in ballistics. The major emphasis of the present work is the calculation of the boundary layer effect on these bodies where both laminar and turbulent flow is present and the calculation of the associated "Magnus effect." Since the Magnus effect results from a spin induced distortion of the boundary layer, this investigation is an attempt to accurately model the boundary layer on bodies of revolution in supersonic flow. Numerical methods have been developed to define the flow field around a yawed body of revolution in terms of laminar, turbulent and mixed boundary layers.

ANALYSIS

The equations governing the three dimensional compressible laminar boundary layer on a rotating body of revolution are simplified by using transformations developed by Moore (Ref. 1). A finite difference form of the transformed boundary layer equations are solved using Newton's method (Ref. 2). The laminar solution is not a realistic representation of the flow field around most bodies of revolution of practical interest because of the free-flight and Reynolds number. Jacobson (Ref. 3) has shown that transition and the onset of turbulence must be considered to provide an accurate description of the flow field. A computer code has been developed (Ref. 4) to analytically predict the transition region. The stability program numerically solved a set of eight first order equations for linear stability of compressible boundary layers. A typical result of this analysis is shown in Figure 1. Here the neutral and the amplified stability curves are plotted as a function of wave number (frequency of the disturbance) and x distance along the length of the body. The neutral stability curve, corresponding to $C_i = 0$, represents the points where the instabilities first begin to occur. The subsequent isocontour curves (C_i = .01, .02) indicate the amplification rates of small disturbances as they propogate along the length of the body. The results of the stability theory are used to predict transition by considering the amplification of small disturbances as they propogate downstream in the flow. The critical growth amplification factor (where transition occurs) is identified by using the experimental measurements of Sturek (Ref. 5). An exponential growth is assumed between the point where the instabilities first occur (near the tip of the body) to the

point where transition to turbulent flow occurs. The regions of laminar, turbulent and mixed boundary layers are identified and mapped on to the surface of the body. A typical transition area is shown in Figure 2. In order to define the boundary layer flow in terms of laminar, mixed and turbulent boundary layers (as shown in Figure 2) the turbulent boundary layer equations must be solved. Eddy viscosity formulation of the turbulent boundary layer are integrated by using Newton's method (Ref. 2).

With the knowledge of the boundary layer flow around a body of revolution, several contributions to the Magnus effect can be considered. The normal and cross flow shear stresses and the centrifugal pressure force contributions are directly calculated from the boundary layer solution. The displacement thickness component of the Magnus effect is calculated using modified slender body theory (Ref. 2).

SUMMARY OF RESULTS AND CONCLUSIONS

A boundary layer/potential flow code has been developed to predict Magnus effect on a spinning body of revolution at an angle of attack. Experimental studies have shown that in order to model the viscous fluid flow over a spinning body of revolution in free flight, the influence of asymmetric transition and the presence of a mixed boundary layer must be considered. These effects, along with the conventional laminar and turbulent boundary layers have been modelled in this study. Magnus coefficients have been numerically computed to study the effects of spin rate, Mach number, angle of attack and the length of the body for each of three boundary layer configurations - fully laminar, fully turbulent and mixed flows. Based on this theoretical study the following conclusions can be drawn.

a) Asymmetric transition and the presence of a mixed boundary layer strongly influences the Magnus force.

b) In the transition region of a mixed boundary layer, the relative magnitude of the normal wall shear stress component (τ_x) can be significant and therefore cannot be neglected as suggested by many theoretical studies in past.

c) The effect of a mixed boundary layer on the Magnus force is most pronounced in the asymmetric transition region. Therefore, if the transition region, on a nose shape, extends to the end of the body, the Magnus effect predicted by using fully laminar or turbulent boundary layers will be in error.

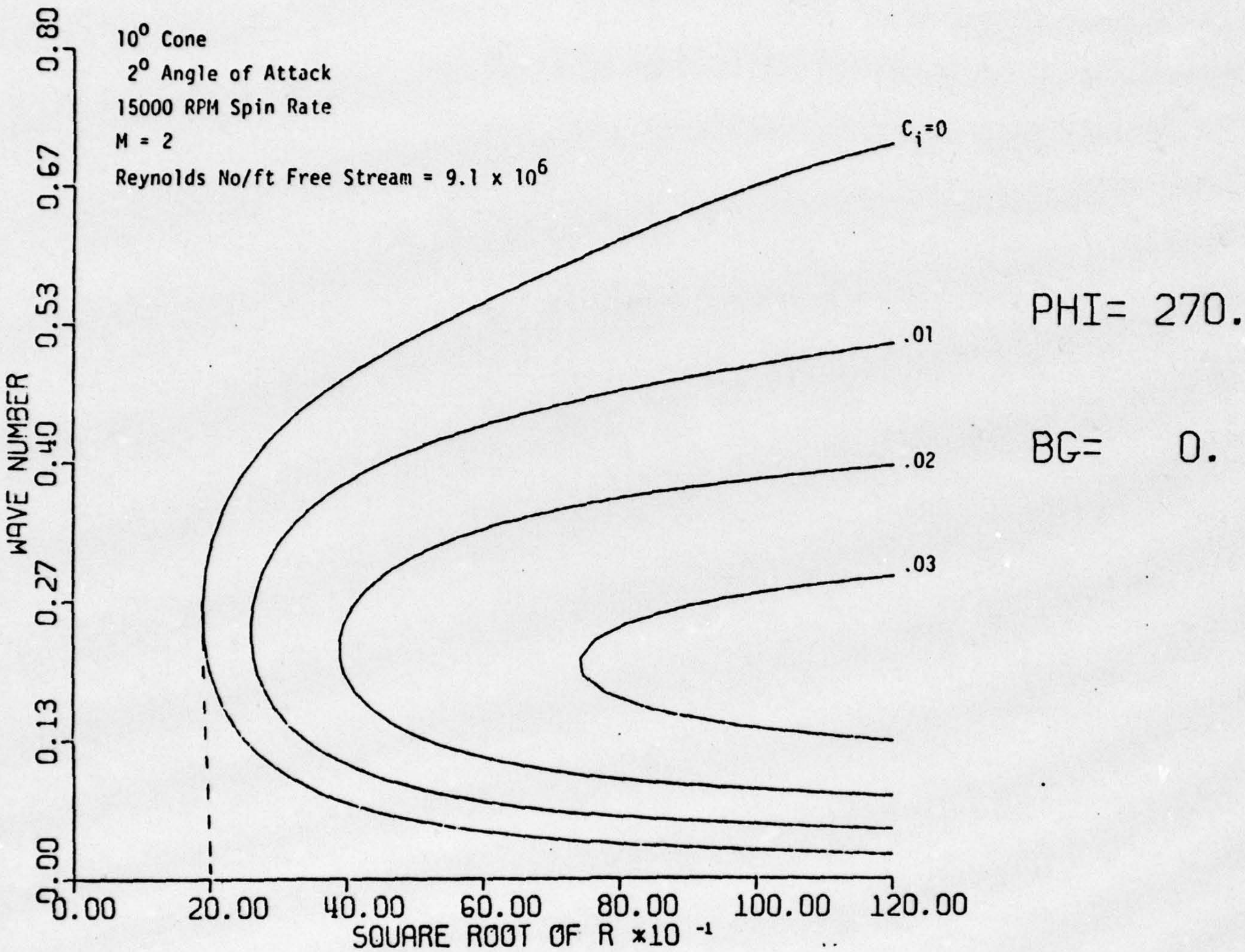

Figure 1 Stability Analysis

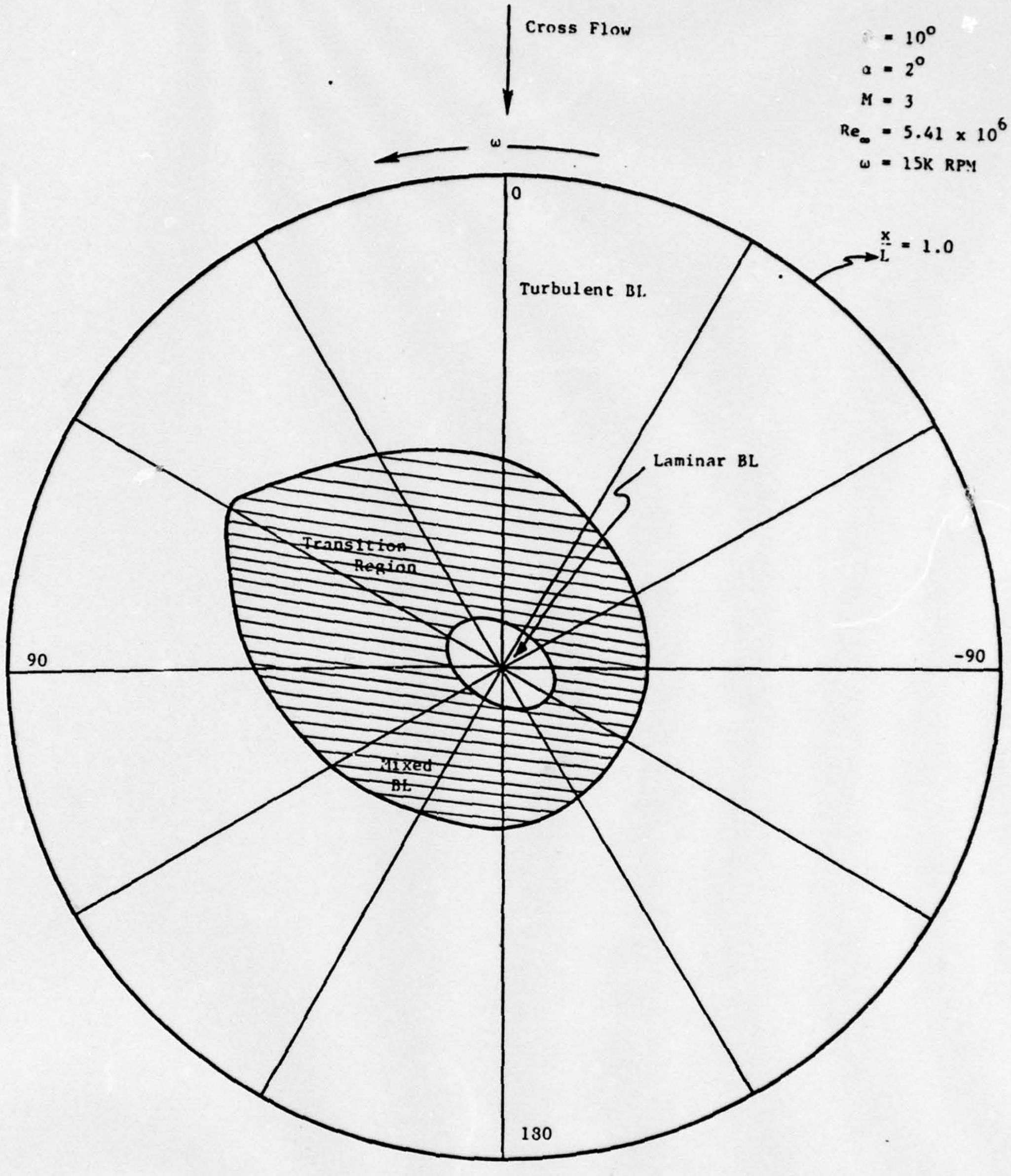

Figure 2 Transition Region

d) In the transonic range, the Magnus effect predicted for mixed boundary layers agrees with the case of fully turbulent flow. However, as the Mach number increases, the discrepancy widens and can turn critical in the hypersonic range. Therefore, in order to adequately model the boundary layer for Magnus studies in the hypersonic range, the influence of asymmetric transition and the presence of a mixed boundary layer must be considered.

e) The Magnus effect shows a strong dependance on angle of attack. At higher angles of attack (4^{o} to 6^{o}) a mixed boundary layer characterized by asymmetric transition is required to accurately model the fluid flow and to predict the Magnus forces and moments.

f) The choice of a suitable boundary layer model critically effects the calculated Magnus characteristics of a spinning body of revolution at an angle of attack.

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